Development of an ASHRAE 152-2004 Duct Model for the Single-Family Residential House

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ABSTRACT

This paper presents the results of the development of the duct model based on ASHRAE standard 152-2004 (ASHRAE, 2004) using the DOE-2.1e building energy simulation program. To accomplish this, FUNCTION commands for DOE-2 were used to develop the duct model and provide the improved predictions of the duct heat loss or gain from the unconditioned space as well as supply or return duct leakage. After applying the duct model to the DOE-2 base-case simulation model, simulation results were compared with the measurement from the case-study house for verification.

INTRODUCTION

In the U.S., there are a number of computer simulation programs that predict the energy use in buildings. However, the inclusion of heat loss or gain through duct systems has received little attention in most simulation programs. For example, EnergyGuage (version 2.42) and eQuest (version 3.60) consider the duct loss but the source code to the duct model in the simulation is not published in the public domain. Even the nationally-supported DOE-2 program (DOE-2.1e, ver. 119) has an over-simplified duct heat loss calculation that is driven only by a constant duct air loss and a constant delta-T heat gain.

ASHRAE developed ASHRAE Standard 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE, 2004) to estimate the seasonal efficiency for residential building systems. This calculation considers the impacts of duct leakage, duct location, duct and attic insulation levels, and climate. For this research, the equations from ASHRAE Standard 152-2004 were applied to the SYSTEMS part of the DOE-2 simulation using FUNCTION commands for DOE-2.1e to incorporate a duct model. This duct model was then incorporated into a DOE-2 model that was calibrated to data from a base-case house, which has installed sensors to measure data to verify the duct model.

METHODOLOGY

Base-case house

The building dimensions and installed equipment were obtained from the architectural drawings of the case-study house and thesis by Kootin-Sanwu (2004). The case-study house located at Bryan, Texas is a single-story Habitat for Humanity house built in 1997. This house has one living room, a dining room, a kitchen, a utility area, 3 bedrooms, 1-½ bathrooms, and a front and back porches. The total conditioned area is 1,150 ft^2. Table 1 shows the specifications of the case-study house.

The heating, ventilation and air-conditioning system consists of a 10.5 SEER (Seasonal Energy Efficiency Ratio) air-conditioning unit (2.5 tons), a furnace with 80% AFUE (Annual Fuel Utilization Efficiency), and a 0.56 EF (Energy Factor) 40-gallon domestic gas hot water system.

Table 1. Material Used in Construction.

	Material
Floor	− 4” uninsulated concrete slab with 30” deep beams, which are 12” wide around the perimeter and spaced approximately 12ft apart on a grid. − Linoleum tile
Exterior walls	− Vinyl siding and ½” plywood wrapped with “Tyvek” moisture barrier − ½“ gypsum, R-13 blown-in treated cellulose insulation − Composite 2x4” stud wall
Interior walls	− 2x4” stud wall − ½ ”gypsum
Ceiling	− 5/8” fire rated gypsum board − 12” of blown-in fiberglass insulation.
Roof	− Composite shingles − 5/8” plywood deck − 2x4” trusses set at 24” centers
Window	− Double pane clear with aluminum frame, without thermal break

A computer model of the as-built case-study house was constructed using the DOE-2.1e program (version 119). The DrawBDL architectural rendering program (Huang and Associates 2000) was used to check the accuracy of the building's geometry in the DOE-2 model. The output of the DOE-2.1e program provided the annual energy use for the building in the Building Energy Summary Report (BEPS), monthly energy use, and hourly energy use. The model of case-study house was divided into an attic zone (unconditioned space) and room zone (conditioned space) (Figures 1 to 2).

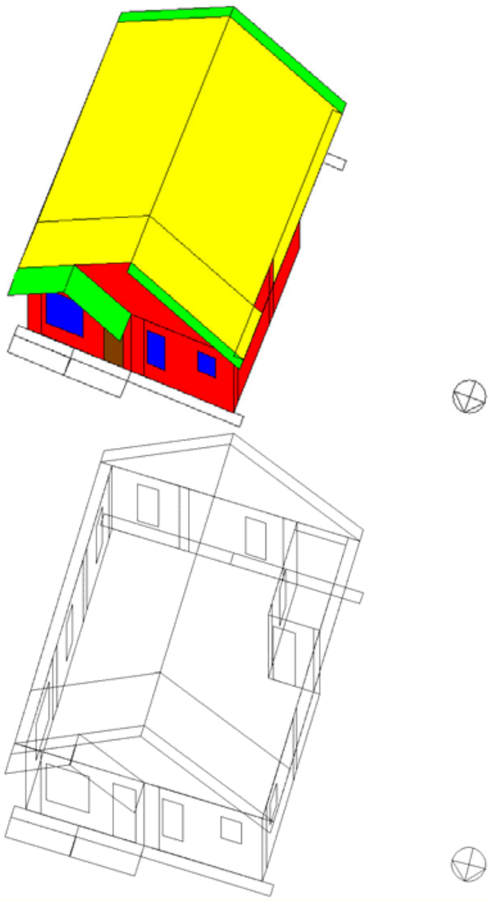

Figure 1. Image of the As-built Case-study House Simulation Input Using the DrawBDL Program.

Base-Case Model Calibration

In order to develop a calibrated DOE-2 simulation of the case-study house, a series of simulations were used to assess the improved accuracy. The calibration process included the comparison of the simulated versus measured hourly attic temperature, zone temperature, electricity use and, natural gas use using a specially prepared weather file that included measured weather data corresponding to the same period as the other measurements. In this simulation, the input model was divided into two adjacent zones, a living space and an attic space (Figure 2). In the base-case model calibration, the attic temperature is critical since the attic space is the direct environmental condition for the duct system. Although there are more advanced attic models that have a radiation network with view factors and buoyancy driven natural ventilation (Spitler et al. 1991), this article relies on the attic model as simulated by DOE-2 program. Therefore, the hourly attic and indoor temperatures were calculated and reported by using the DOE-2 hourly report capability. Table 2 shows the attic temperature calibration process. The calibration process started with the quick mode, which used only equivalent U-values for the building envelope and pre-calculated ASHRAE weighting factors. Then layered materials were added to the base-case model, and DOE-2's Custom Weighting Factors (CWFs) were enabled. Finally, varying air change rates in the attic space were applied to achieve more accurate attic temperatures.

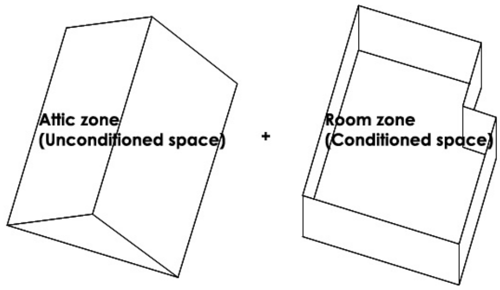

Figure 2. Zones of the As-built Base-case House.

Table 2. Attic Temperature Calibration Process.

Run No.	Summer Period	Winter Period
1	Quick mode, Air-change = 0	Quick mode, Air-change = 0
2	Thermal mass mode, Air-change = 0, Infiltration Schedule = 1	Thermal mass mode, Air-change = 0, Infiltration Schedule = 1
3	Thermal mass mode, Air-change = 5, Infiltration Schedule = 1	Thermal mass mode, Air-change = 5, Infiltration Schedule = 1
4	Thermal mass mode, Air-change = 10, Infiltration	Thermal mass mode, Air-change = 10, Infiltration

	Schedule = 1	Schedule = 1
5	Thermal mass mode, Air-change = 15, Infiltration Schedule = 1	Thermal mass mode, Air-change = 15, Infiltration Schedule = 1
6	Thermal mass mode, Air-change = 20, Infiltration Schedule = 1	Thermal mass mode, Air-change = 20, Infiltration Schedule = 1
7	Thermal mass mode, Air-change = 25, Infiltration Schedule = 1	Thermal mass mode, Air-change = 25, Infiltration Schedule = 1
8	Thermal mass mode, Air-change = 30, Infiltration Schedule = 1	Thermal mass mode, Air-change = 30, Infiltration Schedule = 1
9	Thermal mass mode, Air-change = 25, Infiltration Schedule = (1,7) (1) (8,20) (0.20) (21,24) (1)	Thermal mass mode, Air-change = 25, Infiltration Schedule = (1,7) (0.2) (8,17) (0.40) (18,24) (0.2)

For the first simulation of the attic temperatures, the Coefficient of Variation for the Root Mean Squared Error (CV(RMSE)) was 14.5 %, and the Mean Biased Error (MBE) was 6.9 %. For the living space, CV(RMSE) was 2.5 %, and the MBE -1.3 %. In run #2, actual layered materials with DOE-2's Custom Weighting Factors (CWFs) were added to the base-case model, called the "thermal mass mode", with the same infiltration rate as the quick mode model. This caused the CV(RMSE) and MBE for the attic temperature to be reduced from 14.5 % to 8.0 % and 6.9 % to 2.0 %, respectively.

These results showed that using layered materials with DOE-2's custom weighting factors more accurately predicted the measured temperatures than using an overall U-value and pre-calculated ASHRAE weighting factors.

For the conditioned space, in general, the model predicted the indoor temperatures fairly well since the indoor temperature were relatively constant over the year. From run #3 and run #7, it was found that an attic infiltration schedule of 25 ACH for the nighttime (from 9:00 p.m. to 7:00 a.m.) and 5 ACH for the daytime (from 8:00 a.m. to 8:00 p.m.) yielded the best results. This schedule was used as a substitute for more accurate buoyancy driven convection. Figure 4 shows that the simulated temperatures for run #9 were significantly closer to the actual data than the results of run #1 (Figure 3). In terms of statistical analysis (Figure 5), the CV(RMSE) has decreased from 14.5 % to 5.9 %, and MBE also has decreased from 6.9 % to 0.1 %.

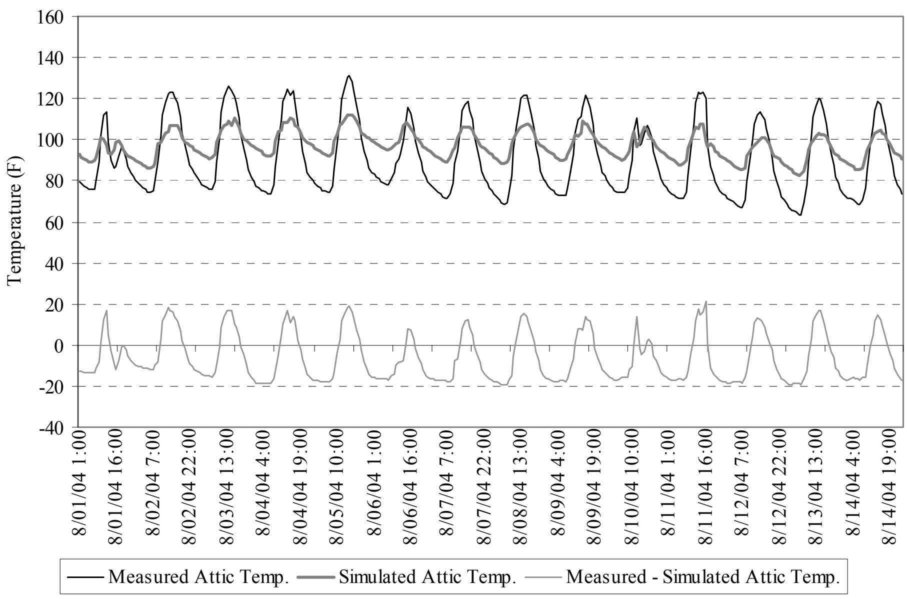

Figure 3. The Uncalibrated Simulation (run #1) and Measured Results of the Attic and Indoor Temperature for the Period August 1 to August 14, 2004 (Continued).

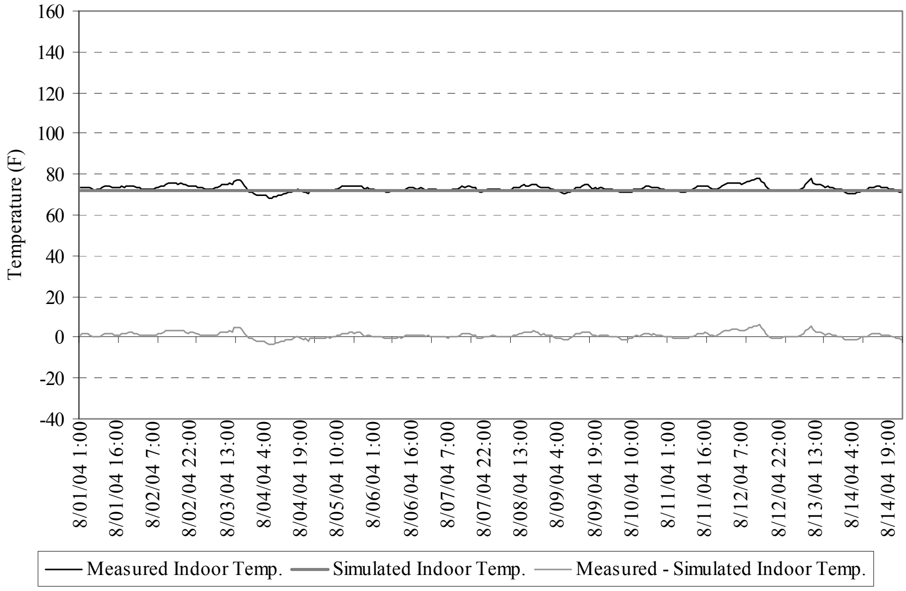

Figure 3. The Uncalibrated Simulation (run #1) and Measured Results of the Attic and Indoor Temperature for the Period August 1 to August 14, 2004.

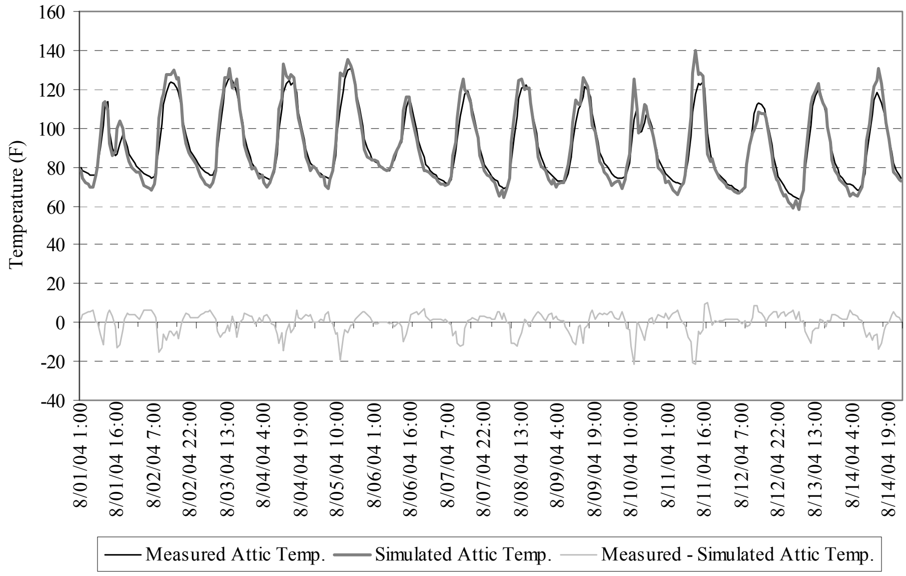

Figure 4. The Calibrated Simulation (run #9) and Measured Results of the Attic and Indoor Temperature for the Period August 1 to August 14, 2004 (Continued).

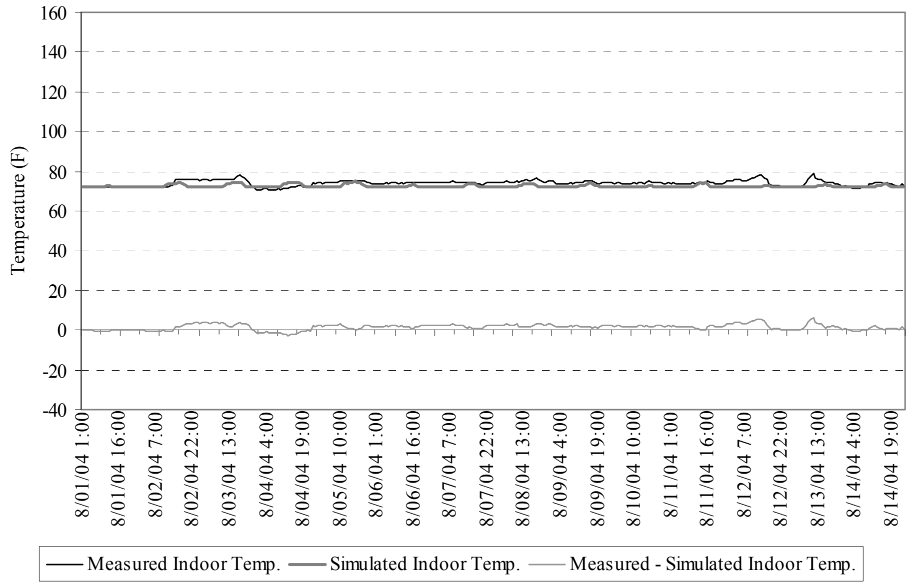

Figure 4. The Calibrated Simulation (run #9) and Measured Results of the Attic and Indoor Temperature for the Period August 1 to August 14, 2004.

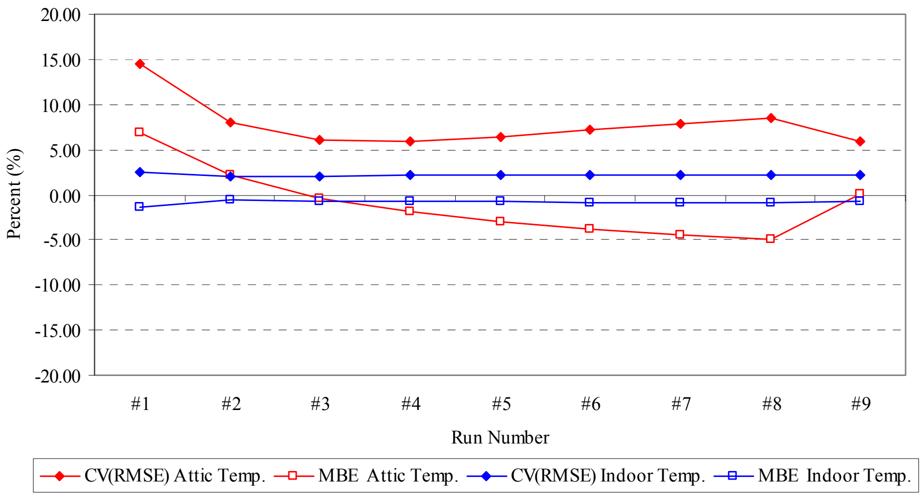

Figure 5. CV(RMSE) and MBE of Attic and Indoor Temperature Calibration for the Period August 1 to August 14, 2004.

The calibration results of the simulation of the attic temperature and indoor temperature for the period December 18 to December 31, 2004 (winter season) are also performed using the similar procedure in the calibration of the summer period.

From Figure 6, the uncalibrated attic and indoor temperatures which were performed using the quick mode, showed constant patterns as the summer period simulation. For the first simulation of the attic temperatures for the winter period, the CV(RMSE) was 14.1 %, and the MBE was -1.7 %. For the living space, CV(RMSE) was 3.3 %, and the MBE was -0.4 %. In run #2, actual layered materials were modeled. The CV(RMSE) for attic temperature decreased to 13.71 % for CV(RMSE), but MBE increased to -4.7 %. Although the MBE of the attic temperatures of run #2 increased, the pattern of the attic temperatures were close to the measured attic temperatures. The reason for the MBE increase is that the measured attic temperature for winter period did not fluctuate as it did for the summer period.

From run #3 and run #4, it was found that an ACH of 5 for the nighttime (from 6:00 p.m. to 7:00 a.m.) and ACH of 10 for the daytime (from 8:00 a.m. to 5:00 p.m.) yielded the best results. Therefore, the modified infiltration schedule was used on run #9. Figure 7 shows that the simulated temperatures were closer to the actual data than the results of run #1 (Figure 6). In terms of statistical analysis, the CV(RMSE) has decreased from 14.1 % to 10.1 %, but MBE has increased from -1.7 % to 6.5 %, which were considered statistically acceptable (Figure 8).

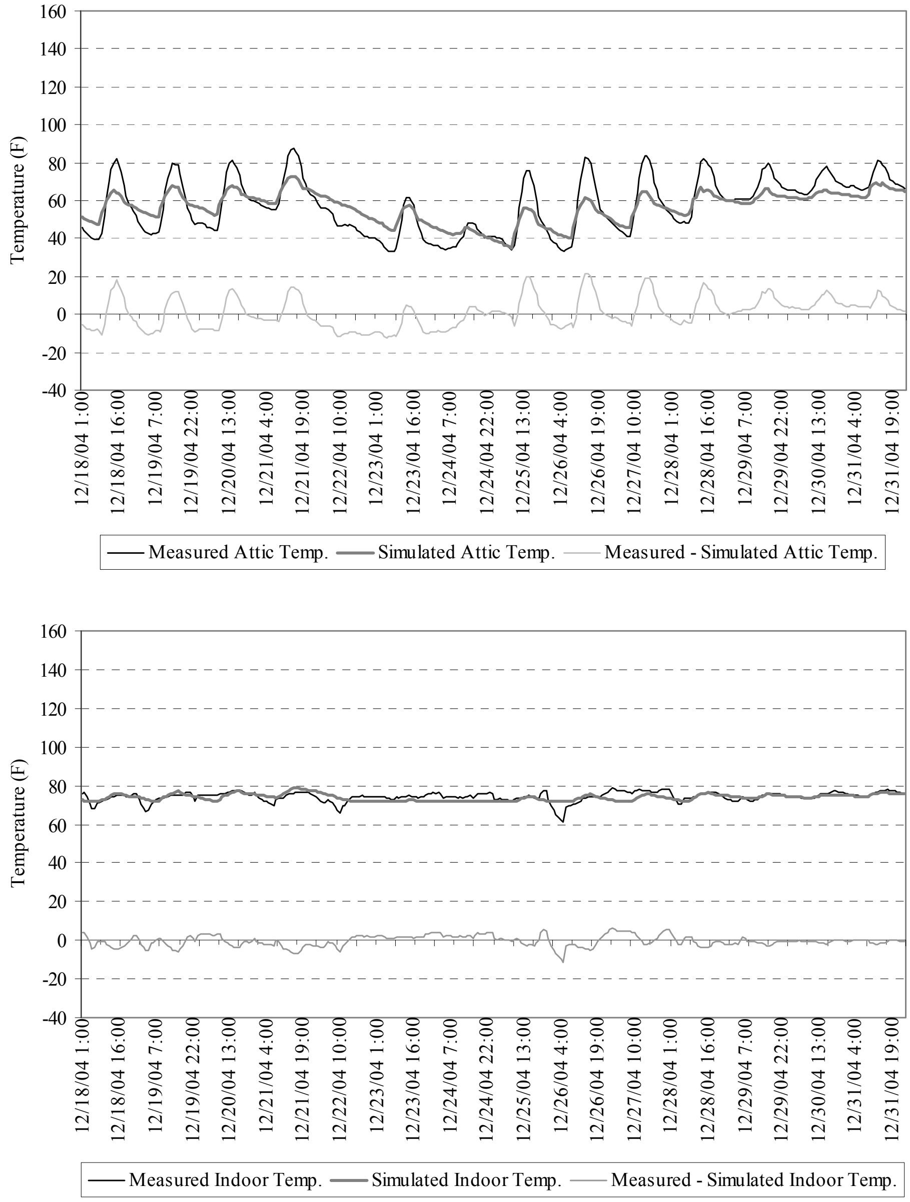

Figure 6. The Uncalibrated Simulation (run #1) and Measured Results of the Attic and Indoor Temperature for the Period December 18 to December 31, 2004.

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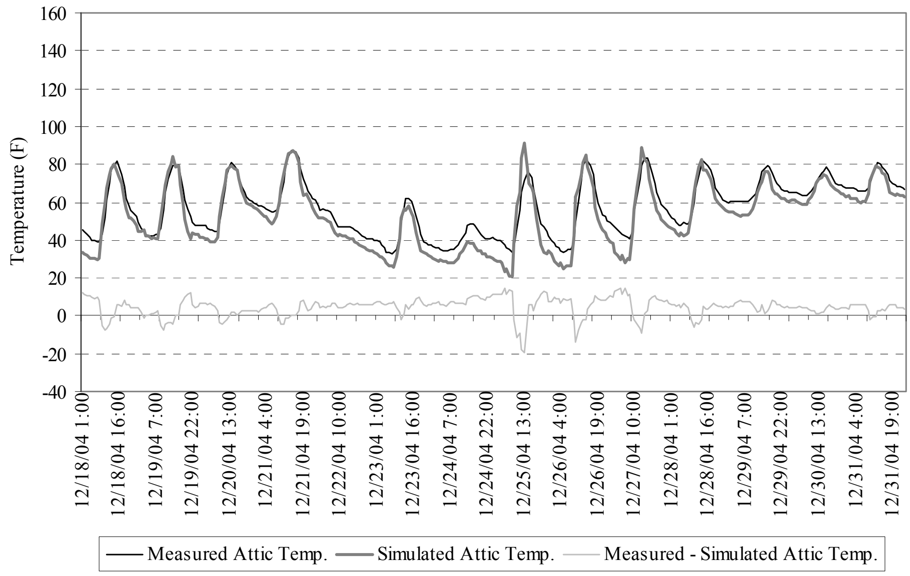

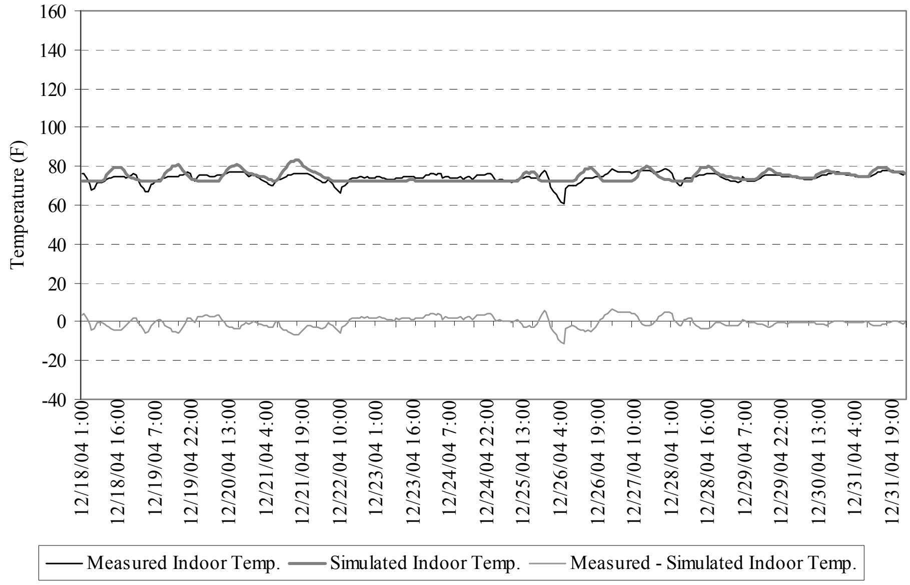

Figure 7. The Calibrated Simulation (run #9) and Measured Results of the Attic Indoor Temperature for the Period December 18 to December 31, 2004.

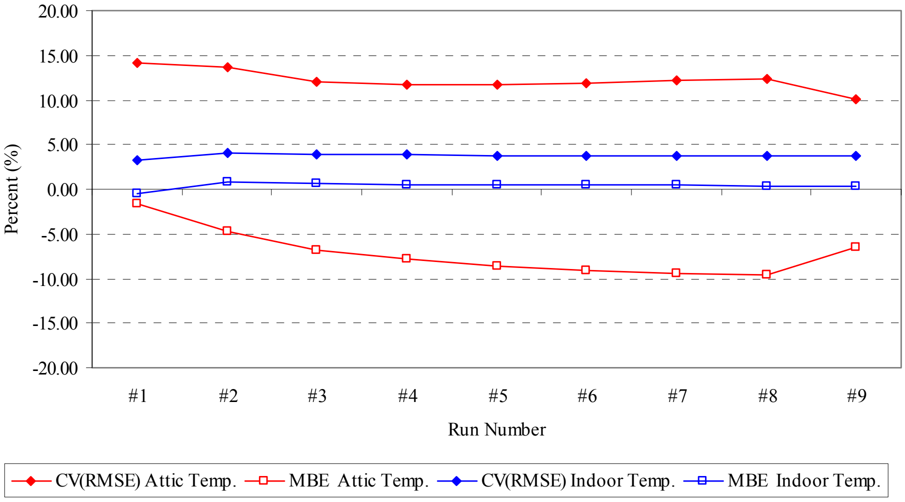

Figure 8. CV(RMSE) and MBE of Attic and Indoor Temperature Calibration for the Period December 18 to December 31, 2004.

Incorporating the duct model

ASHRAE developed ASHRAE Standard 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004) to estimate design and seasonal efficiency for residential building systems. This calculation considers the impacts of duct leakage, location (i.e., attic space, crawl space, etc.), insulation level, climate, etc.

Duct leakage rates in the supply and return sides of the case-study house were assumed as 10% for supply and return sides based on the research by Cummings (1991). Supply air flow (CFM) was 992 CFM obtained from the previous research by Kootin-Sanwoo (2004). For the supply CFM measurement, air-handler fan flow measurements using an Alnor air flow meter were performed.

The following equations show the procedure for the calculation of the delivery efficiency of the heating and cooling systems considering duct conduction loss and air leakage in the supply and return ducts (ASHRAE 2004).

$$DE_{heating} = a_s B_s - a_s B_s (1 - B_r a_r)\frac{\Delta t_r}{\Delta t_e} - a_s (1 - B_s)\frac{\Delta t_s}{\Delta t_e} \quad \text{Eq. 1}$$

$$DE_{cooling} = \frac{a_s Q_e \rho_{in}}{E_{cap}}\left(\frac{E_{cap}}{60 Q_e \rho_{in}} + (1 - a_r)(h_{amb,r} - h_{in}) + a_r C_p (B_r - 1)\Delta t_r + C_p (B_s - 1)(t_{sp} - t_{amb,s})\right) \quad \text{Eq. 2}$$

where,

B_s = conduction efficiency of supply duct $= \exp\left(\frac{-A_s}{60 Q_e \rho_{in} C_p R_s}\right)$, Eq. 3

B_r = conduction efficiency of return duct = $\exp\left(\frac{-A_r}{60 Q_e \rho_{in} C_p R_r}\right)$, Eq. 4

a_s = air leakage efficiency of the duct of supply duct = $\left(\frac{Q_e - Q_s}{Q_e}\right)$, Eq. 5

a_r = air leakage efficiency of the duct of return duct = $\left(\frac{Q_e - Q_r}{Q_e}\right)$, Eq. 6

E_{cap} = capacity of the equipment (Btu/hr),

Q_e = system air flow (CFM),

C_p = specific heat (Btu/(lb$_m$·ºF)),

Δt_e = temperature rise across the equipment (ºF) = $\frac{E_{cap}}{60 Q_e \rho_{in} C_p}$, Eq. 7

Δt_s = temperature difference between the building and the ambient temperature surrounding the supply (ºF) Eq.8

Δt_r = temperature difference between the building and the ambient temperature surrounding the return (ºF) $= t_{in} - t_{amb,r}$, Eq. 9

t_{in} = temperature of indoor air (ºF),

t_{sp} = supply plenum air temperature (ºF),

$t_{amb,s}$ = ambient temperature for supply ducts (ºF),

$t_{amb,r}$	= ambient temperature for return ducts (ºF),
$h_{amb,r}$	= enthalpy of ambient air for return (Btu/hr),
h_{in}	= enthalpy of air inside conditioned space (Btu/hr),
A_s	= supply duct area (ft^2),
A_r	= return duct area (ft^2),
ρ_{in}	= density of air (lb/ft^3),
R_s	= thermal resistance of supply duct ($hr\text{-}ft^2\text{-}ºF/Btu$),
R_r	= thermal resistance of return duct ($hr\text{-}ft^2\text{-}ºF/Btu$).

Figures 9 and 10 show the procedures of the FUNCTION developed for DOE-2 to apply the duct model using the equations of ASHRAE Standard 152-2004. In this procedure three FUNCTIONS are used (SAVETEMP, DUCT, and DUCT 2). 1) The SAVETEMP function saves the calculated buffer zone temperature and conditioned space temperature to send these temperatures to the next function. 2) The DUCT function calculates the delivery efficiency using the saved temperatures, data from the hourly report and user inputs, and it modifies the Energy Input Ratio (EIR) to the air conditioner every hour in proportion to the losses. The concept for this EIR modification came from Huang (2001) 3) The DUCT2 function changes the modified EIR back to the original value for the next hour calculation.

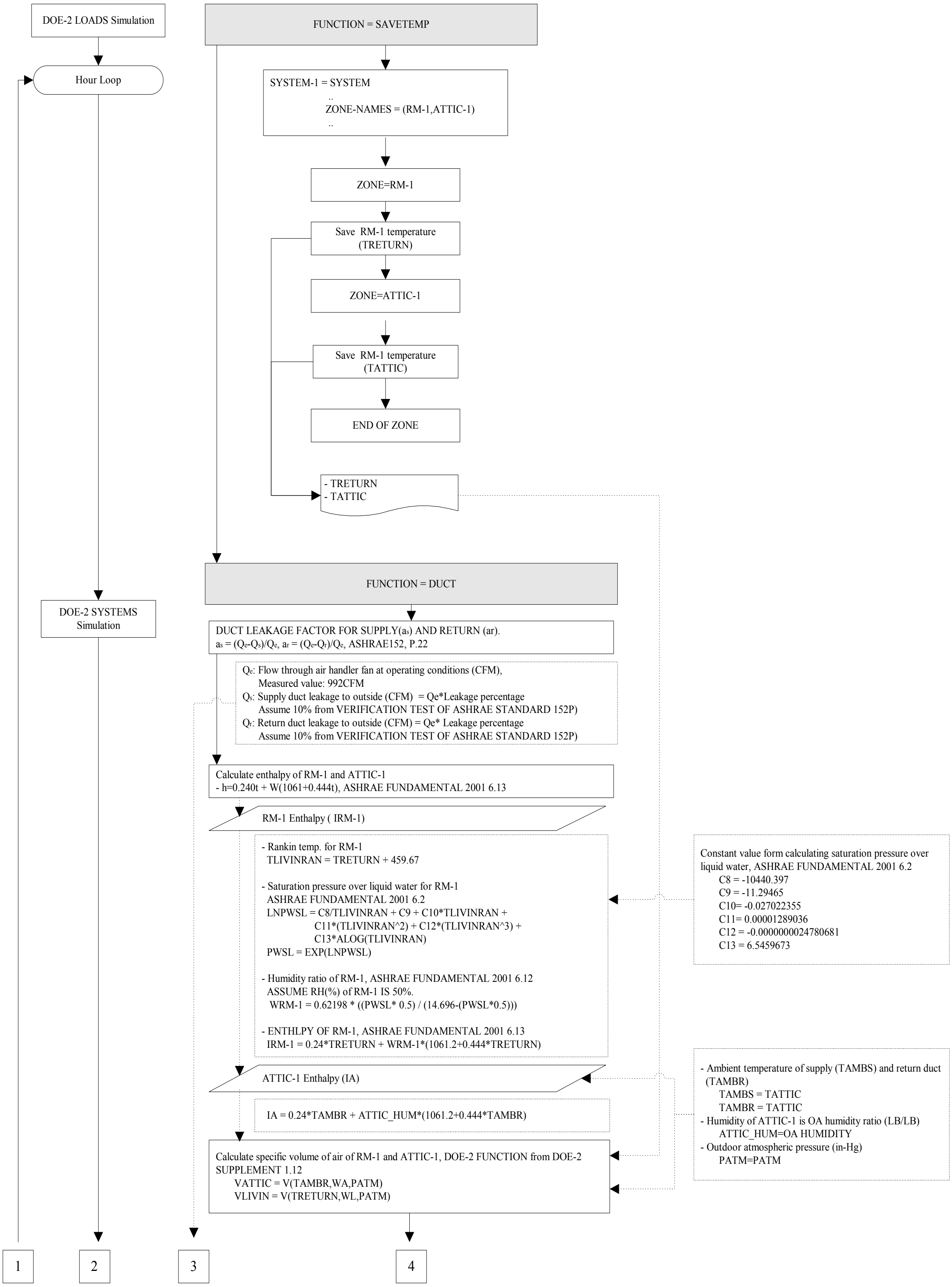

Figure 9. Diagram of DOE-2 FUNCTION Command for ASHRAE 152-2004 Duct Loss Model (a).

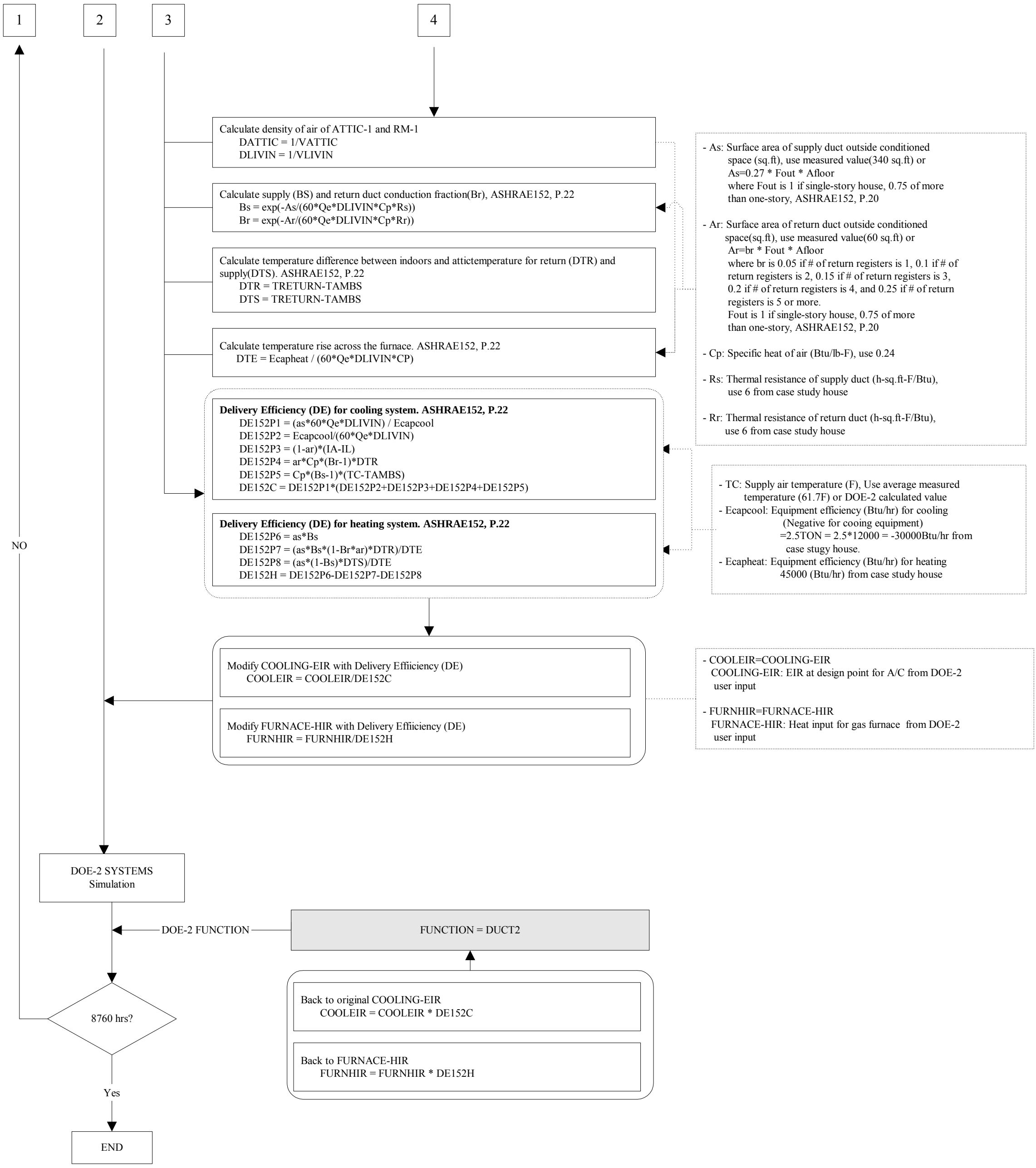

Figure 10. Diagram of DOE-2 FUNCTION Command for ASHRAE 152-2004 Duct Loss Model (b).

RESULTS

Once the calibration of the attic temperature and the indoor temperature were completed, the duct model, which uses ASHRAE Standard 152-2004 was incorporated into the calibrated DOE-2 model. As mentioned before, a more accurate simulation of the attic temperatures was critical, since attic temperature was the direct environmental condition of the duct systems.

Figure 11 illustrates the temperatures, and cooling and heating energy use over the entire year before the duct model was incorporated into the calibrated simulation models. The results show that the measured maximum cooling energy was 3.26 kWh/h (11,111 Btu/hr), but the simulated maximum cooling energy was 1.97 kWh/h (6,730 Btu/hr), since heat gains to the duct system and AHU from the attic space were not considered in this simulation. On average, the measured hourly cooling energy use was 0.72 kWh/h for one-year, but the simulated hourly cooling energy use was 0.46 kWh/h, which was lower than the measured cooling energy use. From the two-week period of data from August 1 to August 14, 2004 (Figure 12), the results show the range of 0.44 kWh/h to 3.20 kWh/h for the measured results and 0.33 kWh/h to 2.48 kWh/h for the simulation results in the cooling energy use, demonstrating major differences between the measured and simulated cooling energy uses.

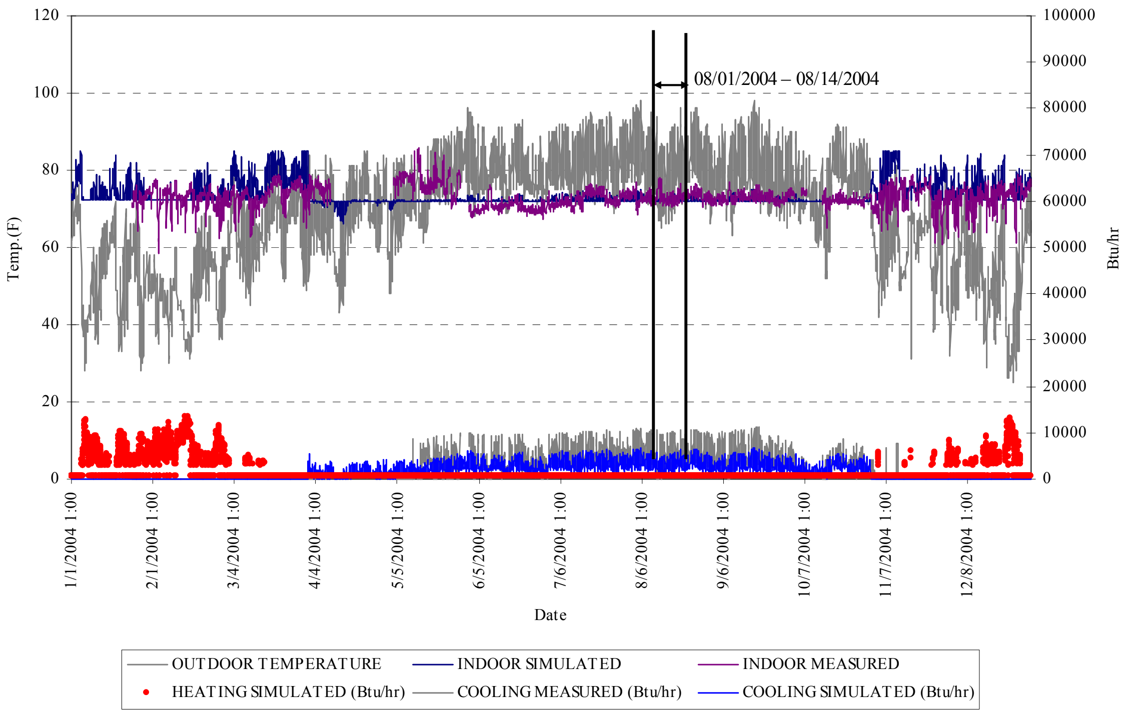

Figure 11. Temperature and Cooling energy Plots without Duct Model for the Whole Year.

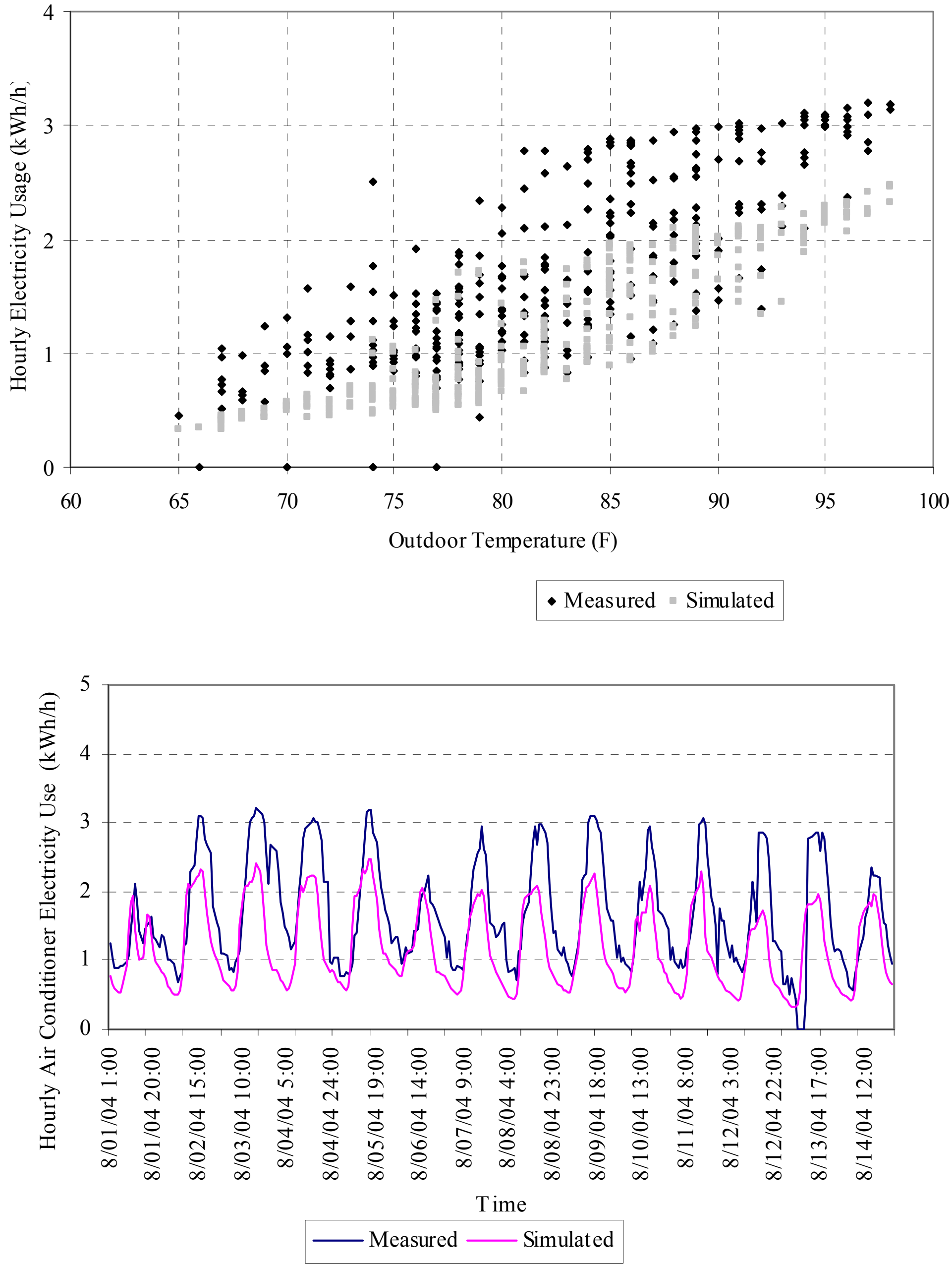

Figure 12. Cooling Energy Plots Without A Duct Model for Two Weeks from August 1 to August 14, 2004.

In terms of statistic analyses, the CV (RMSE) was 40.24 %, and the MBE was -29.10 %, which indicated a lack of agreement. Figures 13 and 14 present results after the duct model was incorporated into the DOE-2 simulation model. In the annual plot (Figure 13), it was found that simulated cooling energy use increased compared to Figure 11, where the duct model was not applied to the DOE-2 simulation model.

On average, the simulated hourly cooling energy increased from 0.46 kWh/h to 0.66 kWh/h after the duct model was added to DOE-2 model. As shown in Figure 14, the range of the simulated cooling energy was 0.38 kWh/h to 3.44 kWh/h after the duct model was incorporated into DOE-2 program, while the range of simulated cooling energy was 0.33 kWh/h to 2.48 kWh/h before incorporating the duct model into the DOE-2 input.

From this plot, it can be seen that the amount of cooling energy use was closer to the measured cooling energy use than the simulation results before the duct model was applied to the DOE-2 simulation model. Furthermore, the CV (RMSE) was reduced from 40.24% to 25.4 %, and the MBE was reduced from -29.10% to -8.25 %, which are considered acceptable.

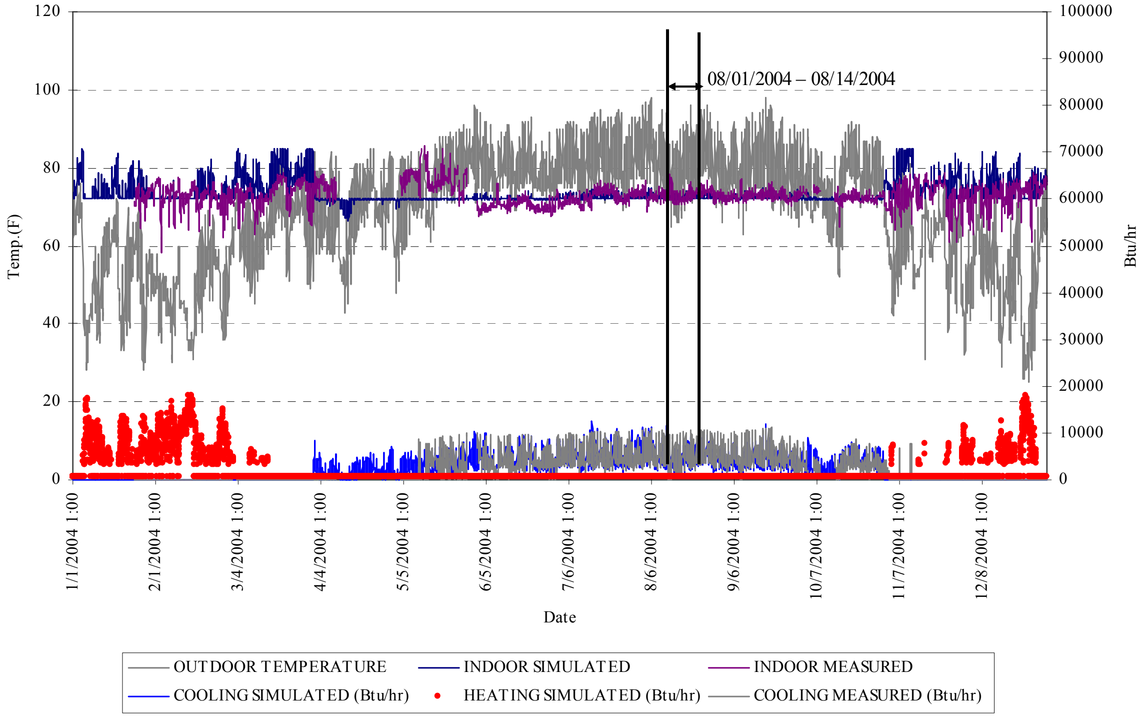

Figure 13. Temperature and Cooling Energy Plots with Duct Model for Whole Year.

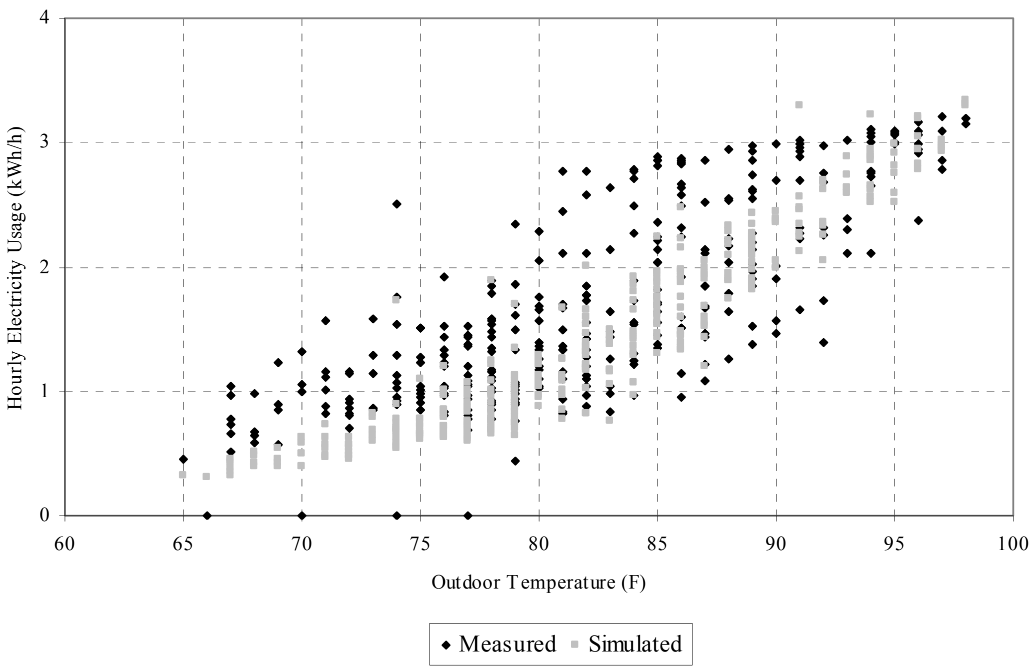

Figure 14. Cooling Energy Plots with Duct Model for Two Weeks from August 1 to August 14, 2004 (Continued).

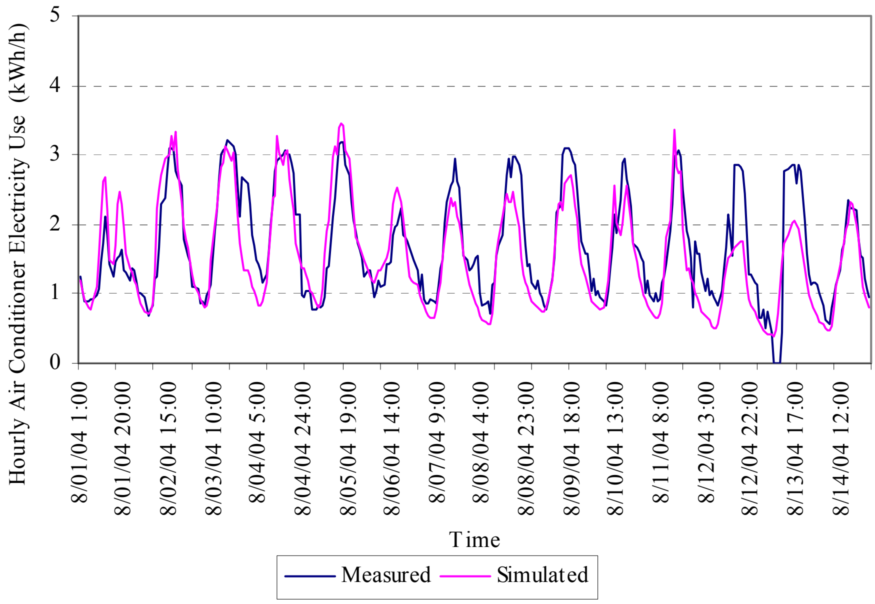

Figure 14. Cooling Energy Plots with Duct Model for Two Weeks from August 1 to August 14, 2004.

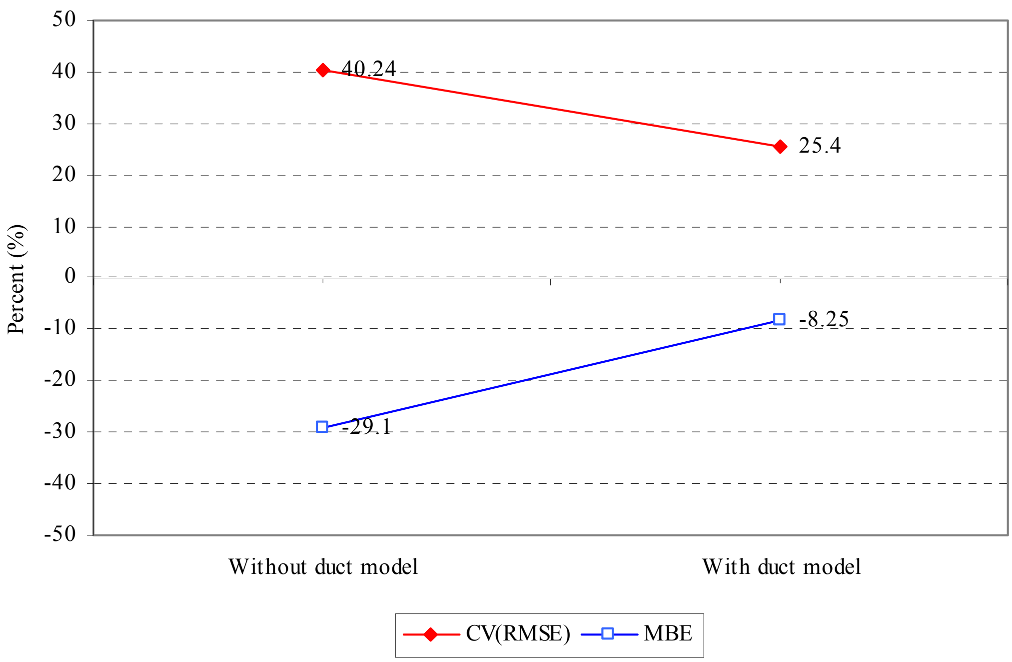

Figure 15. CV(RMSE) and MBE of with and without Duct Model.

DISCUSSION

This paper shows the results of the incorporation of the duct model based on ASHRAE standard 152-2004 (ASHRAE, 2004) using the DOE-2.1e building energy simulation program.

After applying the duct model to the base-case house simulation model, the statistical analysis was performed to compare the simulation results with the measured data. The CV (RMSE) was reduced from 40.24% (without the duct model) to 25.4 % (with the duct model), and the MBE was reduced from -29.10% (without duct model) to -8.25 % (with duct model), which are considered acceptable.

Therefore, the simulation results with the duct model provided a better match to the measured energy use than the previous simulation results that did not include a duct model. Thus the DOE-2 simulation with the duct model provides an improved simulation of the impact of the duct properties in residential energy use, which could not have been considered in the previous DOE-2.1e residential simulation models.

ACKNOWLEDGEMENT

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